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Keywords (separated by '-')	Fiber reinforced concrete - Tension properties - Tension test - Toughness - Quality control
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ORIGINAL ARTICLE

Double Punch Test to control the energy dissipation in tension of FRC (Barcelona test)

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Abstract Current testing methods used to measure tensile properties of Fiber Reinforced Concrete (FRC) are mainly based on bending test of beam specimens. They normally show a considerable scatter that makes difficult the quality control, as in particular when such properties are intended to estimate the strength of structural members. In order to improve the material assessment procedure, the Double Punch Test (DPT) has been recovered for the quality control of the tension behaviour of FRC. Former experimental research showed the feasibility of the test and a reduction of the scatter in the values of the tensile strength and of the toughness. This paper describes the results of an experimental program carried out using both DPT and bending test on FRC with different type of fibers, concretes and fiber contents. In addition, a correlation between both tests is proposed. Its application to steel and polyolefin FRC specimens shows very good results.

Keywords Fiber reinforced concrete · Tension properties · Tension test · Toughness · Quality control

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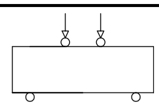
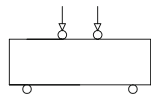
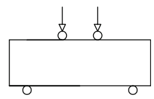
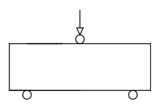
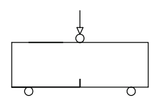
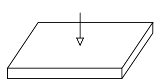
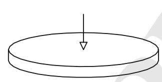
1 Introduction

Most methods currently used to characterize the behaviour of fiber reinforced concrete (FRC) are based on bending tests of prismatic beam specimens, loaded at mid span (3 point test)—European (EN 14651) [1] or with two loads applied each at one third of the span (4 point test)—Belgian (NBN B 15–238) [2] and American (ASTM C-1018) [3]. However, as the Belgian beam test procedure [2] points out in its preface, these tests are not oriented to systematically control the quality of the tensile properties of FRC.

All these tests present a large scatter, frequently over 20% as is shown in Table 1, as in particular in tests with notched specimens such as EN 14651 [1]. The latter test reduces slightly the scatter but it results in more complexity, effort and time-consumption. In addition, as Table 1 summarizes, most bending specimens are comparatively heavier.

To overcome these drawbacks, a research on the application of the indirect tension test of double punching was initiated at the Department of Construction Engineering of the Universitat Politècnica de Catalunya (UPC) at Barcelona. The so called Barcelona test is the extension to FRC of the Double-Punching Test (DPT) formerly presented by Chen [7] to measure the tensile strength of plain concrete. At that time, it was intended as an alternative to the broadly used Brazilian test [8] to determinate the indirect tensile strength. Then, DPT did not supplant the Brazilian test because the latter was slightly easier

Table 1 Comparison of significant parameters of several bending tests and DPT

Test	Layout	Dimensions (cm)	Weight[a] (N)	Failure surface (cm^2)	Specific failure surface	CV[b] (%)
ASTM C-1018		35 × 10 × 10	84.0	100.0	0.0286	15[c]
NBN B 15-238		(60−75) × 15 × 15	405.0	225.0	0.0133	12–20[d]
EFNARC beam		55 × 7.5 × 12.5	123.7	93.8	0.0182	20[e]
3-point bending test		55 × 7.5 × 12.5	123.7	93.8	0.0182	17[f]
RILEM 3-point bending test		(55–60) × 15 × 15	297.0	187.5	0.0152	10–25[g]
EFNARC panel		60 × 60 × 10	864.0	2,597.7	0.0722	9[f]
Round determinate panel		7.5 × ϕ80	906.5	900.0	0.0238	6–13[f]
Double Punch Test		15 × ϕ15	63.6	337.5	0.1274	13[h]

[a] Estimated supposing a specific weight of 24 kN/m^3

[b] CV is the coefficient of variation

[c] CV of the ASTM index of toughness ASTM I_{30} evaluated by Bernard [4]

[d] CV of the flexure strength $f_{f,300}$ on NBN tests from Saludes [5]

[e] CV of the residual strength at 3.0 mm of deflection in the centre of the panel, Bernard [4]

[f] CV of toughness parameter evaluated by Bernard [4] in specimens of sprayed SFRC

[g] CV of the parameters measured on concrete specimens with 25–75 kg/m^3 of steel fiber content [6]

[h] CV of toughness of concrete specimens of 25 kg/m^3 of steel fiber content [5]

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and, as a consequence, cheaper than DPT. However, while Brazilian test cannot be applied to measure tensile properties of FRC, DPT can successfully be applied to FRC, as is here in presented.

In addition, much research has been made on the contribution of FRC to the ultimate capacity of structural members. In this context, the authors consider that there is a need to develop an efficient—easy and reliable—test to systematically control the tension properties of FRC, in particular, when its tension strength is taken into account in the structural capacity. Results of a previous feasibility research on the application of Barcelona test (BCN test) to FRC have yet been presented [9].

In this paper, results obtained by the BCN test are checked with those provided by the Belgian beam test [2] using different fiber types and varying the fiber content. To that purpose, a simplified model that theoretically correlates the results of both tests is developed and, then, applied to the experimental results.

The procedure to implement BCN test to control tensile properties of FRC starts from a characterization of the FRC using beam test and, later, obtaining the correlation between both tests from an experimental program that varies the fiber content. Then, BCN test simplifies the control procedure of tensile properties. Since 2007, Barcelona test is being used in the concrete quality control of the segments for the lining of the subway line 9 nowadays under construction in Barcelona.

2 Barcelona test and its correlation with beam tests

2.1 Main characteristics of Barcelona test

The BCN test [9] and [10] consists of compressing a cylindrical fiber reinforced concrete specimen placed vertically within two steel circular punches centred at the top and bottom surfaces (Fig. 1). Normally, the height and the diameter are identical (2b/2h = 1) and the ratio between the diameters of the punches and the specimen is one fourth (2a/2b = 0.25). The failure mechanism (Fig. 2) normally presents three radial cracks, although in some cases four planes can be observed. The specimens tested during the research presented in this paper were 150 mm height

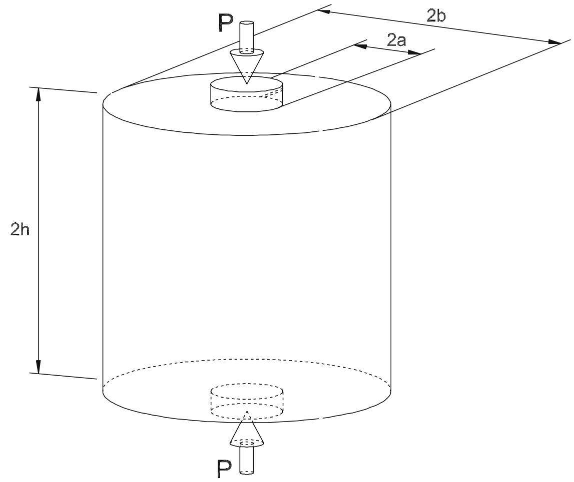

Fig. 1 Barcelona test layout

and were obtained by halving a 300 mm height cylindrical cast sample.

Previous research had demonstrated that normal working errors (5 mm eccentric placing of the punches) presented no noticeable effect on the results [10]. Also, inverting up-down the position of the moulded face didn't affect the results.

The main advantages of BCN test are that it produces (a) material saving (Table 1) and, thus, it is more environment friendly; (b) time saving and, thus, economy; (c) results with less standard deviation than those obtained by bending tests or direct tension test, owing to its larger value of specific failure surface, as shown in Table 1; (d) lighter specimens; and (e) it allows testing bored specimens to assess the tension properties of actual FRC structural members.

2.2 Equivalence between Barcelona and beam tests

The equivalence between both tests is faced in terms of energy absorption for the different measured parameters: load versus vertical displacement in the bending test [2] and load versus circumferential deformation at mid height of the specimen in the BCN test [5].

To obtain this relation, it is necessary to define the Total Circumferential Opening Displacement (*TCOD*) measured as a circumferential opening ($\Delta\phi$) for Barcelona test and the vertical deflection (δ) for bending test which provides the same average crack opening (w) in both tests. Next paragraphs describe the approaches required to achieve that relation.

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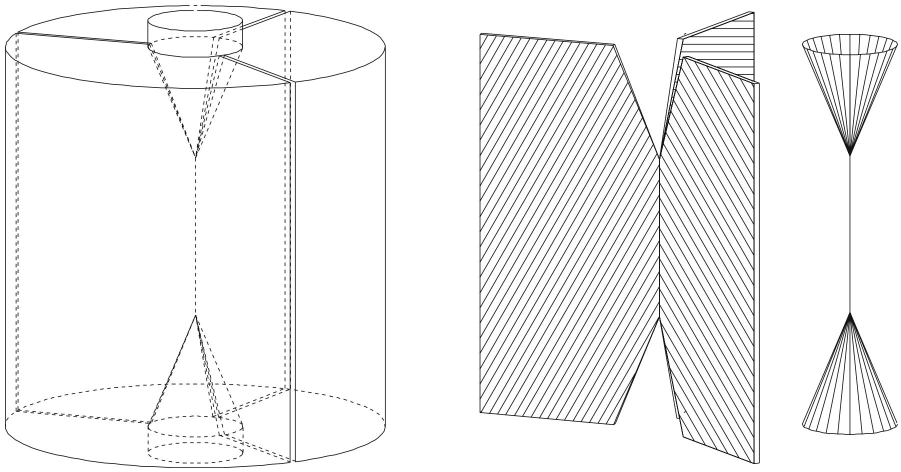

Fig. 2 Barcelona test mechanism of failure and failure surfaces

Assuming that after cracking in bending there is only one crack close to mid span and the height of the crack is almost the depth—and, thus, the two halves rotate in a hinge—(Fig. 3), it is possible to obtain a geometrical relation between the vertical deflection and the crack width. This relation, assuming that the angles are small, is:

$$\theta = \frac{\delta}{l} \Rightarrow \theta = \frac{w/2}{h} = \frac{w_{NBN}}{h} \tag{1}$$

where h is the depth of the prismatic specimen, l the half span, δ the vertical deflection, θ the rotation on the supports, w the crack tip opening displacement and w_{NBN} the average crack opening in the whole cracking surface. In particular, and taking into account that the size of the specimen in the Belgian bending test is 150 × 150 × 600 mm and, thus, the depth (h) is 150 mm and the half span (l) 225 mm, expression 1 yields,

$$w_{NBN} = \frac{w}{2} = \frac{2}{3} \cdot \delta \tag{2}$$

It is worth noting that the assumptions made are much realistic when cracks are enough wide, as in the case of FRC specimens which present very much ductility after cracking, because it neglects the elastic deformation of the un-cracked segments of the specimen.

A similar geometrical relation between *TCOD* ($\Delta\phi$) and average crack opening can be worked out for BCN test. To that purpose, a failure mechanism of three radial cracks that present a similar width is assumed, as shown in Figs. 2 and 4. The little cones next to the punches are neglected according to the results of Bortolotti [11] and Marti [12]. Experiments normally show three cracks but they normally do not present the same width. However, the main interest of the assumption over the width of cracks is to correlate results between both tests.

The failure mechanism presented in Figs. 2 and 4 also shows how the crack opening is uniform across every radial crack, which is in very good agreement with the experiments. According to the assumptions described, the relation between the average crack opening and the *TCOD* is:

$$\Delta\phi = 3 \cdot w_{BCN} \tag{3}$$

where $\Delta\phi$ is the *TCOD* and w_{BCN} the average width of the radial cracks.

The comparison between the total circumferential opening displacement of the BCN test and the vertical deflection of the Belgian bending test is based on the average crack opening. To the authors point of view, this has full physical sense because it compares similar crack widths. Imposing that average crack width in the BCN test (w_{BCN}) is the same in the Belgian test (w_{NBN}), yields

$$w_{BCN} = \frac{\Delta\phi}{3} = w_{NBN} = \frac{2}{3} \cdot \delta \tag{4}$$

Equation 4 gives the values at which the energy absorption has to be comparable because it corresponds to similar average crack opening.

In the proposed correlation, toughness in BCN test is measured from cracking at peak loading because

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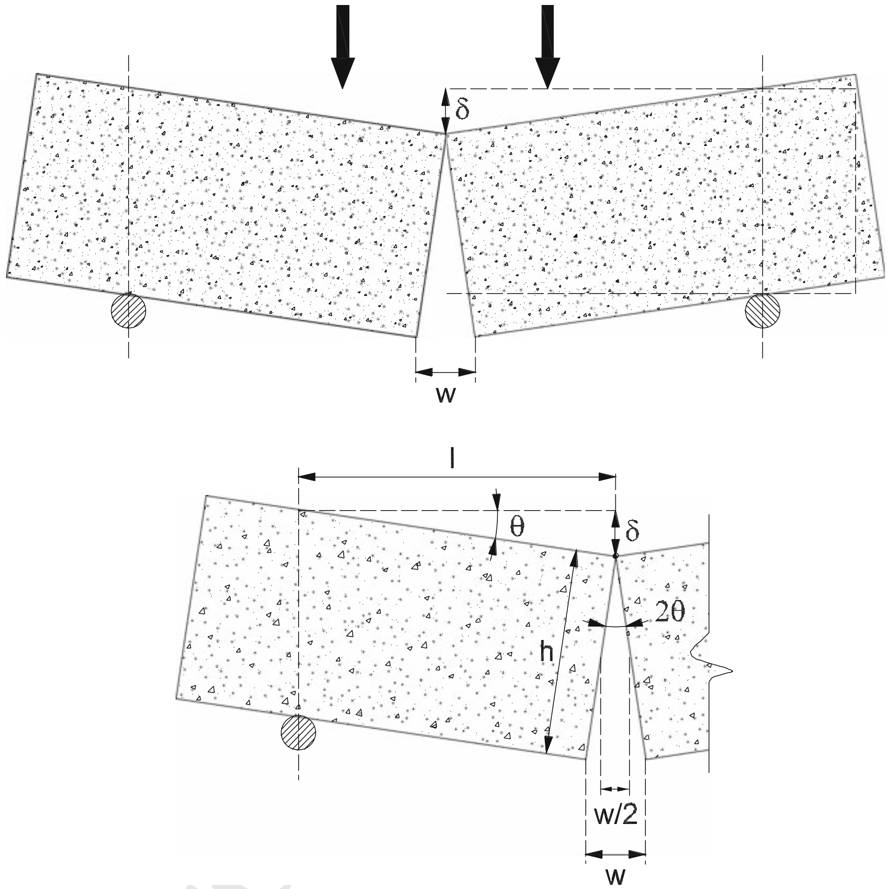

Fig. 3 Ideal kinematics assumed for the Belgian beam test [2] after cracking and geometrical parameters involved

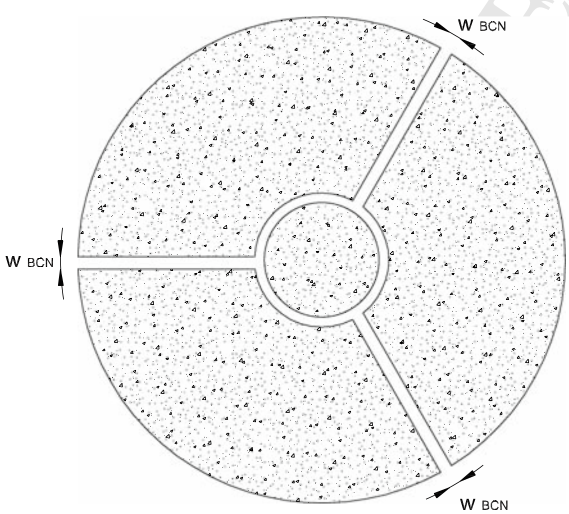

Fig. 4 Ideal cracking layout assumed for BCN test

till that moment the circumferential opening is negligible (around 0.03 mm) while in the Belgian test, energy absorption is measured from the beginning of the test (Eqs. 5 and 6). This fact does not disturb the final result because in the latter, peak loading and cracking appear at very small values of vertical deflection and, thus, the amount of energy measured till peak loading is very small.

$$E_{NBN}(\delta_n) = \int_0^{\delta_n} P(\delta)\, d\delta \qquad (5)$$

$$E_{BCN}(TCOD_n) = \int_0^{TCOD_n} P(TCOD)\, d(TCOD) \qquad (6)$$

where P is the applied load in the test, $E_{BCN}(TCOD_n)$ is the toughness measured at a determined value of $TCOD$ and $E_{NBN}(\delta_n)$ is the energy measured at a determined value of δ.

However, the possible distortion that the cones of the failure mechanism of BCN test (Fig. 2) can introduce in the correlation between this test and the

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Belgian beam test deserves some concern. According to the analyses carried out by Marti [12] for plain concrete Double Punch Test, the amount of the energy dissipated in the little cones under the punches was about 27% of the total energy. So, much energy is put in causing the radial cracks. There is no evidence of similar studies of DPT applied to FRC, but it can be assumed that their distortion does not affect significantly the correlation between both tests.

3 Experimental program

To appraise experimentally the effectiveness of BCN test and its correlation with the Belgian bending test, two experimental series were developed on two different concretes. The aim of series 1 was to analyze the influence of different type of fibers in a concrete of 40 N/mm^2 of characteristic compressive strength. Series 2 was intended to analyze the influence of fiber contents in a 25 N/mm^2 concrete. Tests were developed at 28 days in both series. The number of specimens tested in each determination was larger for the Belgian bending test owing to its larger standard deviation [10]. In the BCN test, both Total Circumferential Opening Displacement (*TCOD*) and vertical displacement between loading plates were measured. *TCOD* was measured by a circumferential extensometer placed at mid height of the specimen, as shown in Fig. 5. The test was controlled by the vertical displacement between the plates of the press at a rate of 0.5 mm/min. Figure 5 also shows the usual cracking pattern on the upper and cylindrical faces obtained in the test.

3.1 Series 1: influence of the type of fiber

For this series, concrete from the precast segments of the new Line 9 of the Metro of Barcelona, now under construction, was used. In particular, the material of series 1 was actually used to build segments in an experimental section placed in the *Bon Pastor* Station in section 4b of Line 9. Design compressive strength of concrete was 40 N/mm^2 and its consistency was plastic. Fiber types and contents were:

- modified polyolefin straight fibers 48 mm long at a dosage of 5 and 6.5 kg/m^3 referenced with BK5 and BK6.5, respectively. Its rectangular cross section presents an embossed surface to improve bonding with concrete.
- steel fibers 50 mm long with hooked ends at a dosage of 25 kg/m^3 referenced with W25. Its cross section was circular.

Table 2 shows the geometrical and material properties of fibers used in both series.

Each series (BK5, BK6.5 and W25) was composed of eight (8) cylindrical specimens of $\phi150 \times 150$ mm for BCN test, tested at 28 days, and twelve (12) beam specimens of $150 \times 150 \times 600$ for Belgian beam test,

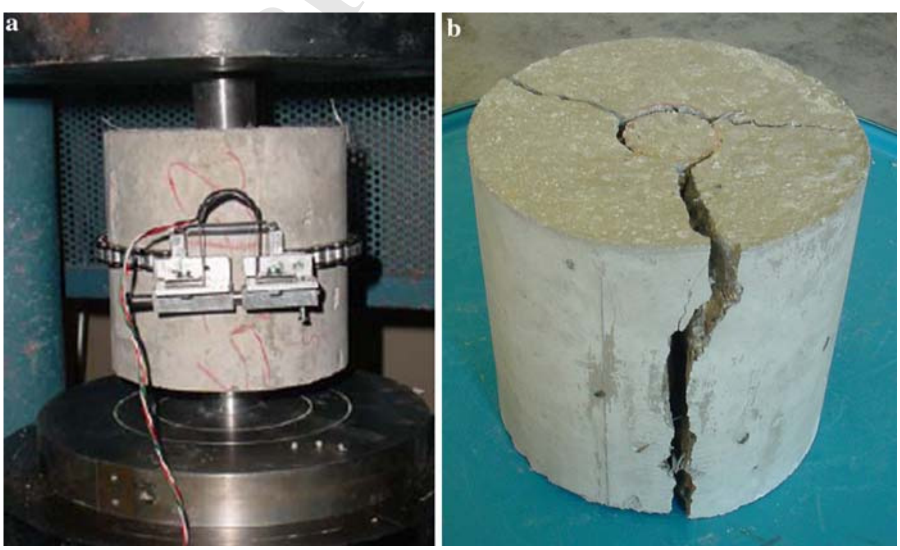

Fig. 5 Specimen placed on the press ready to be tested (**a**) and the specimen after testing (**b**)

Table 2 Properties of steel and synthetic fibers used in series 1 and 2

Series	Reference	Material	Density (g/cm^3)	Aspect ratio	Section (mm^2)	Number of fibres per kg	Tensile strength (N/mm^2)	Surface area per fiber (mm^2)
1	BK5 & BK6.5	Synthetic	0.91	53	0.656	34,722	560	193
	W25	Steel	7.85	66.6	0.441	5,767	1,100	117
2	B20, B30, B40 & B50	Steel	7.85	47.6	0.866	2,942	1,000	165

Table 3 Mixture proportion and compressive strength of series 1 concrete

Mixture proportion per m^3	W25	BK5	BK6.5
Gravel 1 (14–22 mm) (kg)	559		
Gravel 2 (5–14 mm) (kg)	558		
River sand (0–5 mm) (kg)	746		
Cement (c) I52.5R (kg)	400		
Water (w) (kg)	152		
w/c	0.38		
Admixture: Viscocrete 20 HE (kg)	0.8		
Fiber (kg)	25 steel	5.0 synthetic	6.5 synthetic
Average compressive strength (28 d.) (N/mm^2)	62.0	60.2	55.6
Coefficient of variation	5.4%	4.9%	5.8%

tested at the same age. All specimens were cured at a temperature of 20°C ± 2°C and at a relative humidity over 95% until testing. Table 3 shows the mixture proportion of all specimens: BK5, BK6.5 and W25.

3.2 Series 2: influence of the fiber content

For series 2, conventional concrete of building structures was used, with a characteristic compressive strength of 25 N/mm^2 and a plastic consistency. Hooked ends steel fibers 50 mm long and 1.05 mm of diameter were employed using 20, 30, 40 and 50 kg/m^3 contents, with reference B20, B30, B40 and B50, respectively. Table 2 shows the geometrical and material properties of the fibers employed in this series.

All tests were made at the age of 28 days. For each fiber content, three (3) cylindrical specimens of $\phi 150 \times 300$ mm were tested in compression, six (6) cylindrical specimens of $\phi 150 \times 150$ mm were tested by BCN test and nine beam specimens of 150 × 150 × 600 m were tested according to NBN B 15-238 [2]. All specimens were cured at 20°C ± 2°C and a relative humidity over 95% until testing. Table 4 shows the mixture proportion of each batch: B20, B30, B40 and B50, which present tiny differences introduced mainly to improve the workability of concrete. The origin of all aggregates was limestone.

Table 4 Mixture proportion and compressive strength of series 2 concrete

Mixture proportion per m^3	B20	B30	B40	B50
Gravel 12–20 mm (kg)	800	790	780	770
Gravel 5–12 mm (kg)	85			
Sand 0–2 mm (kg)	190			
Sand 0–5 mm (kg)	830			
Cement (c) I42.5R (kg)	300			
Water (w) (kg)	170			
w/c	0.57			
Steel fiber (kg)	20	30	40	50
Admixture Melcret pf 77 (kg)	2.0	2.2	2.4	2.4
Average compressive strength (28 d.) (N/mm^2)	37.8	32.2	32.2	35.9
Coefficient of variation	2.2%	2.2%	3.3%	2.2%

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4 Correlation of the energy measured in both tests

4.1 Series 1: influence of the type of fiber

Figure 6 shows the typical load *TCOD* diagram obtained by BCN test. Surprisingly, such diagrams were quite similar in all mixes of the series 1. Table 5 shows the average results of both toughness measures of BCN test and energy measures of Belgian beam test [2]. Despite toughness measure in BCN test starts when cracking and energy in beam test begins when loading, such different origin of measurements does not affect the results because energy measure during elastic loading in beams is almost negligible.

Results show that for each *TCOD* of BCN test or each δ of beam test, toughness of BK5, BK6.5 and W25 are quite similar. This fact demonstrates firstly that the selected type and content of synthetic fibers is almost equivalent to the steel ones and, secondly, that the increase of the content of synthetic fibers from 5 to 6.5 kg/m^3 is ineffective.

When comparing the tests, it can be observed that the energy is larger for BCN test. This is related to the amount of cracking surface which is much larger in BCN test than in the beam test. However, the proportion between energies is larger than between cracking surfaces because BCN test requires much energy during the initial cracking in order to create the cones under the punches. This large energy influences favourably by reducing the scatter of the results. In general, coefficients of variation (CV) for the maximum load in the BCN test were smaller than those obtained in the beam tests (Table 5). However, the CV of energy values do not show a clear tendency. In particular, for W25 BCN test show less

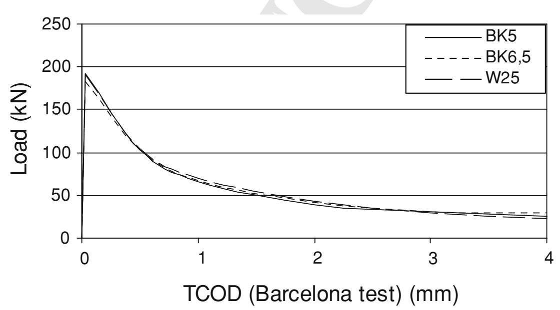

Fig. 6 Average load *TCOD* diagrams obtained by BCN test in series 1 (BK5, BK6.5 and W25)

Table 5 Maximum loads and toughness measures of BCN test and energy measures of NBN B 15-238 [2], both in N/mm, of series 1 at 28 days

	Maximum load (kN)	Barcelona: *TCOD* (mm)				Maximum load (kN)	NBN B 15-238: δ (mm)			
		1	2	3	4		0.5	1.0	1.5	2.0
BK 5	192.0 (9.7%)	114.7 (21.6%)	167.2 (21.0%)	202.0 (16.0%)	230.0 (13.6%)	35.39 (10.7%)	18.3 (17.8%)	31.6 (16.6%)	43.2 (17.9%)	55.0 (20.9%)
BK 6,5	183.0 (7.2%)	113.2 (23.1%)	167.5 (25.9%)	203.8 (23.6%)	233.8 (22.5%)	35.67 (6.0%)	13.68 (10.1%)	22.98 (16.9%)	35.22 (9.7%)	46.79 (11.4%)
W 25	191.0 (6.2%)	116.3 (11.1%)	173.3 (11.5%)	209.8 (12.2%)	236.0 (13.1%)	44.16 (20.8%)	18.32 (25.9%)	31.57 (26.8%)	43.23 (24.7%)	55.03 (24.6%)

Coefficients of variation are in brackets

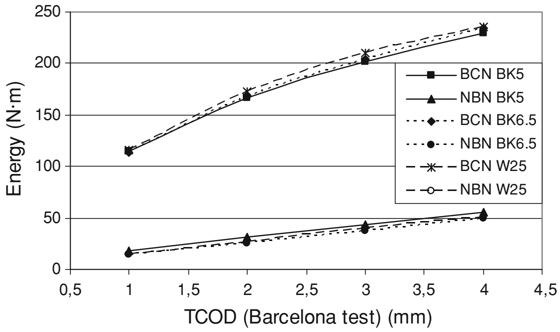

Fig. 7 Average equivalent energy diagrams obtained with both Barcelona and beam tests

scatter than the beam whilst for BK 6.5 is the contrary. For BK 5 the scatter is similar in both tests.

Figure 7 shows the diagrams of the average values of the Table 5 for *TCOD* of 1–4 mm of BCN test and the equivalent values of beam test. The amount of energy of beam test is almost linear with the vertical deflection (δ). However linear behaviour of toughness with *TCOD* only appears at significant values of *TCOD*, as could be expected according with the aforementioned significant amount of energy required to create the cracks at the cones.

Figure 8 shows the result of applying linear regression between the average values of toughness of BCN test (E_{BCN}) and the average values of energy of beam test (E_{NBN}), for fixed values of *TCOD* (1, 2, 3 and 4 mm) and for the equivalent vertical deflection respectively. A good correlation between both BCN test toughness and beam test energy was found (Eq. 7).

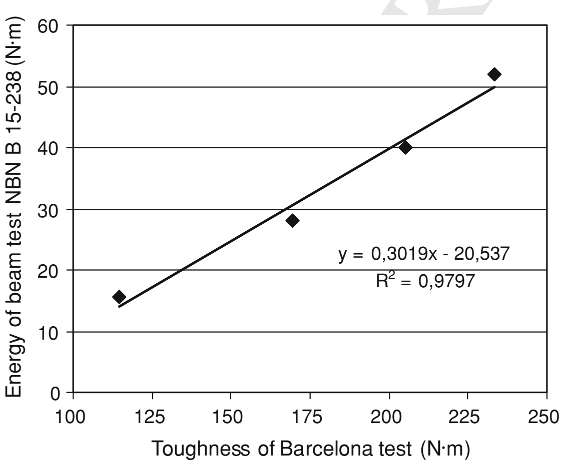

Fig. 8 Linear regression between average values of E_{BCN} and E_{NBN} for equivalent values of *TCOD* of series 1 tests (BK5, BK6.5 and W25)

$$E_{NBN} = 0.302 \cdot E_{BCN} - 20,537 \quad \text{(in N/mm)} \tag{7}$$

4.2 Series 2: influence of the fiber content

To develop the experimental program of series 2, a procedure similar to series 1 was selected. Table 6 shows the results obtained from BCN and beam tests for four different fiber contents. In this series, the range of *TCOD* was increased till 6 mm to compare results with vertical displacements of 3 mm from the Belgian beam test [2].

Toughness and energy results of Table 6 are also represented in Figs. 9 and 10. They show that toughness of BCN test increases with the fiber content. In addition, it can be observed that the fibers contribution is more perceptible for large values of *TCOD*. For example, only slight differences in energy terms are observed for *TCOD* of 1.5 mm whilst for 6 mm there are sharp differences. The same comment can be applied to the vertical displacement in the beam test, as could be expected. BCN test on B30 specimens produced results close to those of B20, breaking the tendency of increment of the toughness with the fiber content (Fig. 9). An experimental determination of the fiber content in two of the specimens which produced lower results showed contents of 22 kg/m^3, showing that there was a problem in the distribution of fibers.

Similarly to series 1, the relation between energy and vertical displacement is linear for the beam test while in BCN test, linear relation of toughness with *TCOD* only appears at significant values of *TCOD*.

Data analysis of series 2 also included, for each fiber content, linear regression between the values of toughness of BCN test (E_{BCN}) and the values of energy of beam test (E_{NBN}), for fixed values of *TCOD* (1.5, 2, 3 and 6 mm) and for the equivalent vertical deflection, respectively. Figure 11 represents graphically the linear correlations for each fiber content. Numerical values of the correlations are summarized in Table 7.

It can be observed that α coefficient shows some dependency on the fiber content while β coefficient remains almost constant and shows no dependency with the fiber content and fiber type (see also Eq. 7 and Fig. 8). It can be observed that the α coefficient of B30 brakes the dependency of such coefficient on the fiber content. This strange value is due to the low

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Table 6 Maximum loads and toughness measures of BCN test and energy measures of Belgian beam test [2], in N/mm, of series 2 at 28 days

	Maximum load (kN)	Barcelona test: $\Delta\phi$ (mm)				Maximum load (kN)	Beam test: δ (mm)			
		1	2	3	6		0.75	1.0	1.5	3.0
B20	122.9 (3.24%)	70.12 (8.3%)	120.1 (9.5%)	158.0 (9.6%)	234.0 (9.8%)	31.27 (4.03%)	11.93 (13.7%)	15.93 (14.7%)	24.72 (14.6%)	52.33 (13.5%)
B30	110.1 (6.35%)	69.31 (11.1%)	120.2 (11.4%)	160.0 (11.3%)	246.6 (11.4%)	32.63 (6.66%)	17.52 (10.8%)	23.81 (12.7%)	36.64 (14.7%)	73.03 (15.9%)
B40	111.5 (4.26%)	76.72 (7.5%)	137.1 (4.9%)	184.3 (3.1%)	283.9 (17.9%)	35.62 (13.0%)	20.51 (24.3%)	28.17 (23.6%)	42.60 (20.2%)	79.07 (14.8%)
B50	117.4 (7.48%)	82.00 (9.3%)	148.6 (10.8%)	201.0 (12.1%)	305.6 (13.8%)	36.15 (3.82%)	22.34 (16.4%)	30.57 (17.0%)	46.48 (16.9%)	87.66 (16.0%)

Coefficients of variation are in brackets

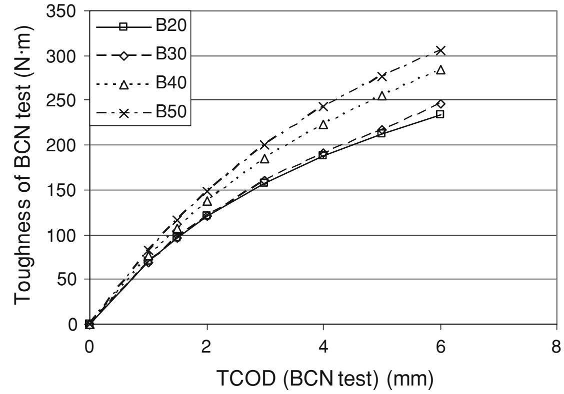

Fig. 9 Toughness—*TCOD* diagram obtained by BCN test for series 2

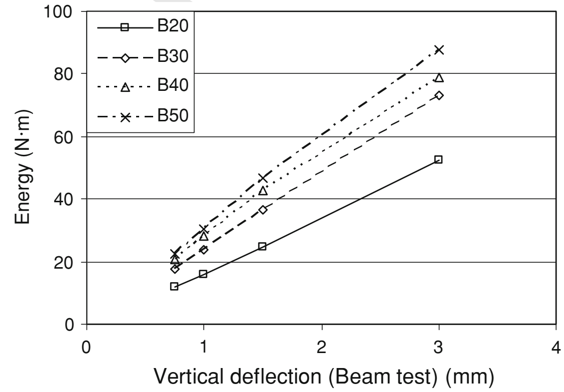

Fig. 10 Energy—vertical deflection diagram obtained by beam test for series 2

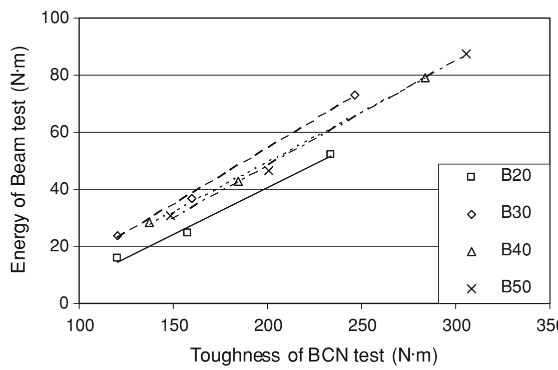

Fig. 11 Linear regression between average values of E_{BCN} and E_{NBN} for equivalent values of *TCOD* of series 2 tests (B20, B30, B40 and B50)

energy values obtained in the BCN test performed, as is previously explained. The coefficient β can be related to the different mechanism developed in both

Table 7 Coefficients of the linear regressions developed for each fiber content of series 2

Fiber content (kg/m^3)	$E_{NBN} = \alpha * E_{BCN} - \beta$		R^2
	α	β	
20	0.300	19.448	0.9809
30	0.375	20.648	0.9927
40	0.337	17.510	0.9963
50	0.350	20.700	0.9932

tests. In fact, BCN test requires more energy to initiate cracking because it demands much more cracking surface.

The dependency of the slope of the correlation, coefficient α, on the fiber content can be attributed to the complex effects that take place around the conical surfaces, including friction and dowel action of fibers actually bridging the cracking surfaces.

5 Conclusions

Double Punch Test for FRC—Barcelona test—offers several advantages to the experimental measurements of the tensile properties of concrete subjected to tension in terms of maximum load and toughness. Such advantages are mainly economical, environmental and also technical. The later ones are related to the lower coefficients of variation that were obtained in most cases when compared with beam tests.

The correlation found between the Barcelona and the Belgian beam tests [2] for fiber reinforced concrete ascertains the equivalence between both tests in terms of energy absorption. This correlation is based on comparing energies for similar average crack opening displacements, despite these measured energies are of different type.

The experimental program, including different types of fibers and concrete and different fiber contents, showed that the Barcelona test is suited to control the tensile properties of FRC. However, further experimental and theoretical work is required to extent this test to the characterization of tensile properties in fiber reinforced concrete.

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